Monthly Notices of the Royal Astronomical Society

Mon. Not. R. Astron. Soc. **400,** 2122–2127 (2009) doi:10.1111/j.1365-2966.2009.15605.x

Imprint of galaxy clustering in the cosmic gamma-ray background

Shin'ichiro Ando⋆ and Vasiliki Pavlidou⋆†

California Institute of Technology, Pasadena, CA 91125, USA

Accepted 2009 August 24. Received 2009 August 24; in original form 2009 April 16

ABSTRACT

Star-forming galaxies are predicted to contribute considerably to the cosmic gamma-ray background (CGB) as they are confirmed γ-ray emitters and are the most numerous population of γ-ray sources, although individually faint. Even though the *Fermi Gamma-ray Space Telescope* will be able to resolve few star-forming galaxies individually, their fractional contribution to the CGB should become far more significant than it was for past measurements of the CGB as many of the brighter, formerly unresolved sources will be resolved out. Thus, the clustering feature of galaxies imprinted on the CGB might be detectable by *Fermi*. In anticipation of such measurements, we calculate the predicted angular auto- and cross-power spectra of the CGB from normal galaxies. We find that the amplitude of the auto-power spectrum is smaller than that for other sources, such as blazars and dark matter annihilation; the shape is also characteristic. We also show that the cross-power spectrum with galaxy surveys features larger amplitude. *Fermi* should be able to detect the correlation signature in both the auto- and cross-power spectra at angular scales of $\sim 1^\circ$–10° after 5 years of operation. Such a detection would be valuable in confirming the level of the star-forming galaxy contribution to the CGB and, more importantly, in serving as a tool in the effort to discriminate between possible origins of the CGB.

Key words: galaxies: evolution – cosmology: theory – large-scale structure of Universe – gamma-rays: theory.

1 INTRODUCTION

Star-forming galaxies are confirmed γ-ray sources. They emit γ-rays produced in hadronic interactions between cosmic ray nuclei and interstellar gas, and in leptonic interactions between cosmic ray electrons and secondaries with interstellar gas and light (e.g. Stecker 1970, 1973; Fichtel & Kniffen 1984; Dermer 1986; Strong, Moskalenko & Reimer 2000). Diffuse emission from the Milky Way is, in fact, the brightest feature of the γ-ray sky, as demonstrated by *SAS-2* (Kniffen et al. 1973), *COS-B* (Mayer-Hasselwander et al. 1982), the Energetic Gamma-Ray Experimental Telescope (EGRET) onboard the *Compton Gamma-Ray Observatory* (Hunter et al. 1997) and by the first-light results of *Fermi Gamma-ray Space Telescope* (Ritz et al. 2009). Other than the Milky Way, the only star-forming galaxy detected in γ-rays is the Large Magellanic Cloud (Hartman et al. 1999), because normal star-forming galaxies are individually faint in γ-rays (Pavlidou & Fields 2001). However, star-forming galaxies are very numerous, and their collective emission is likely to make a substantial contribution (Pavlidou & Fields 2002, hereafter PF02) to the cosmic gamma-ray background (CGB), measured with the EGRET (Sreekumar et al. 1998).

The Large Area Telescope (LAT) onboard *Fermi* will further refine the CGB measurement with improved energy and angular resolutions, whereas it will detect at most three additional galaxies as individual sources (Small Magellanic Cloud, M 31 and maybe M 33; Pavlidou & Fields 2001). Therefore, normal galaxies would be a guaranteed source of the CGB for the *Fermi*–LAT, and their contribution would be at essentially the same level as it was for the EGRET. Other contributors such as blazars, on the other hand, will be substantially reduced with respect to their fractional contributions to the EGRET CGB (Stecker & Salamon 1999), as the *Fermi*–LAT will resolve many of them ($\gtrsim$1000, depending on the luminosity function; see e.g. Narumoto & Totani 2006; Dermer 2007; Inoue & Totani 2009). Normal galaxies also have a characteristic spectral feature – a peak, tracing the hadronic origin of their emission. As a result, when the (more spectrally featureless) blazar contribution is reduced, the contribution from normal galaxies to the CGB could be dominant at energies around a few hundred MeV (PF02),[1] which allows for an almost contamination-free set of photons.

⋆E-mail: ando@tapir.caltech.edu (SA); pavlidou@astro.caltech.edu (VP)
†Einstein Fellow.

[1] Note that while PF02 found that the normal galaxies were likely to have a maximal contribution to the total CGB energy flux at energies $\sim$1 GeV, this result was a consequence of the 'GeV excess' in the EGRET measurement of the Milky Way spectrum which recent *Fermi* observations in mid-Galactic latitudes have not reproduced (Abdo et al. 2009) implying it was likely an instrumental effect. In this work, we use a Milky Way spectrum compatible with no GeV excess and find the normal-galaxy peak to reside at lower energies (see Section 2).

Galaxies are clustered following the large-scale matter distribution in the Universe, and this clustering feature should be imprinted on the CGB. The anisotropy of the CGB has recently been studied theoretically by a number of authors, in order to look for signatures of various contributing sources, such as blazars (Ando et al. 2007a,b), galaxy clusters (Ando et al. 2007a; Miniati et al. 2007), Type Ia supernovae (Zhang & Beacom 2004) and dark matter annihilation (Ando & Komatsu 2006; Ando et al. 2007b; Cuoco et al. 2007; Hooper & Serpico 2007; Cuoco et al. 2008; Lee, Ando & Kamionkowski 2009; Siegal-Gaskins 2008; Taoso et al. 2008; Ando 2009; Fornasa et al. 2009; Zavala, Springel & Boylan-Kolchin 2009). The same approach should also be taken for the normal star-forming galaxies. Should this signature be detected in the *Fermi*–LAT data, it would be extremely useful in a variety of ways.

(i) *As a consistency check.* If an energy range is identified spectrally where the normal-galaxy contribution to the CGB is believed to be strongly dominant, then the CGB photons in this range *must* exhibit anisotropy properties consistent with our understanding of normal-galaxy clustering.

(ii) *As a powerful tool to disentangle multiple CGB components.* Instead of having the CGB strongly dominated by normal galaxies in some energy range, an equally likely scenario is to have a balanced mixture of normal-galaxy photons and photons from different source classes. In this case, as much information as possible is needed to disentangle the different CGB contributions. In this context, the angular power spectrum is as important a clue as the shape of the energy spectrum of the contributions from different populations (see e.g. Siegal-Gaskins & Pavlidou 2009 on how the two can be combined when information from the energy spectrum alone is insufficient to break the degeneracy between different components). The importance of the angular power spectrum in the case of normal galaxies is further emphasized because their clustering properties are very well constrained through galaxy surveys (e.g. Cole et al. 2005; Maller et al. 2005; Percival et al. 2007).

(iii) *As a complement to anisotropy studies of other populations.* As normal galaxies provide a guaranteed contribution to the CGB for *Fermi*–LAT, the CGB anisotropy due to normal galaxies is also a guaranteed background to any anisotropies studies using the diffuse background. For this reason, it is important to calculate the anisotropy properties of the normal-galaxy signal and understand its uncertainties and its sensitivity to input parameters and assumptions.

In this paper, we seek to calculate the expected angular correlation of the CGB signature due to γ-ray emitting normal star-forming galaxies. We consider two quantities: the angular auto-power spectrum of the CGB ($C_\ell^{\gamma\gamma}$) and the angular cross-power spectrum between the CGB map and some galaxy catalogue ($C_\ell^{\gamma g}$). An advantage of the auto-power spectrum analysis is that it can be performed immediately after *Fermi*–LAT has obtained a sufficiently deep all-sky γ-ray map, with γ-ray data alone. As such, it does not suffer from uncertainties introduced through the use of galaxy catalogues, such as issues of completeness and dust corrections. On the other hand, even given the additional uncertainties mentioned above, taking the cross-correlation between the CGB map and a galaxy catalogue provides, as it turns out, a better way to detect the normal-galaxy angular signature, because of the large statistics of the large-scale galaxy surveys.

This paper is structured as follows. In Section 2, we discuss the model we adopt to calculate the contribution of normal star-forming galaxies to the γ-ray background. In Section 3, we calculate the predicted angular auto-power spectrum from star-forming galaxies, and in Section 4 we discuss the cross-correlation between the normal-galaxy component of the CGB and galaxy catalogues. We summarize and discuss our conclusions in Section 5.

2 GAMMA-RAY BACKGROUND FROM NORMAL GALAXIES

We follow PF02 to derive a formulation for the mean CGB intensity from normal galaxies. We adopt their assumptions, and update our calculation with more recent determinations of the cosmic star formation history and Milky Way γ-ray spectrum.

The CGB intensity for photons with energy E (in units of photon number per unit area, time, solid angle and energy range) is given by

$$I(E) = \frac{c}{4\pi}\int \mathrm{d}z \frac{\dot{n}_{\gamma,\mathrm{com}}[(1+z)E, z]}{H(z)}, \tag{1}$$

where $\dot{n}_{\gamma,\mathrm{com}}$ is the comoving γ-ray emissivity density and $H(z)$ is the Hubble function. We assume that the differential γ-ray luminosity (photons per time per unit energy range) simply scales as star formation rate $\psi(z)$ and gas-mass fraction $\mu(z)$:

$$L_\gamma(E, z) = \frac{\psi(z)}{\psi_{\mathrm{MW}}}\frac{\mu(z)}{\mu_{\mathrm{MW}}} L_{\gamma,\mathrm{MW}}(E), \tag{2}$$

where the quantities with the subscript 'MW' represents those for the Milky Way. With the comoving number density of galaxies n_{gal}, the emissivity is then

$$\dot{n}_{\gamma,\mathrm{com}}(E, z) = L_\gamma n_{\mathrm{gal}} = L_{\gamma,\mathrm{MW}}(E)\frac{\dot{\rho}_*(z)}{\psi_{\mathrm{MW}}}\frac{\mu(z)}{\mu(0)}, \tag{3}$$

where $\dot{\rho}_*(z) \equiv \psi(z) n_{\mathrm{gal}}$ is the global star formation rate density.[2] Now, assuming that the sum of gas mass and star mass is constant in the typical galaxy, the gas-mass fraction is simply given by

$$\mu(z) = 1 - (1-\mu_{\mathrm{MW}})\frac{\int_\infty^z \mathrm{d}z(\mathrm{d}t/\mathrm{d}z)\dot{\rho}_*(z)}{\int_\infty^0 \mathrm{d}z(\mathrm{d}t/\mathrm{d}z)\dot{\rho}_*(z)}. \tag{4}$$

Thus, given the cosmic history of the star formation rate density, one could compute $\mu(z)$ by backwards de-evolving the present-day Milky Way gas-mass fraction, μ_{MW}. The assumption of a total baryonic mass of galaxies staying constant in time is not necessarily realistic, as star formation is partly fuelled by newly accreted gas (Prodanović & Fields 2008). However, the overall effect of the details of the gas fraction evolution is relatively small (∼factor of 2; PF02). A more realistic modelling of the evolving gas fraction, including the effects of infall, will be addressed in an upcoming publication.

For the present study, we adopt a model given by Hopkins & Beacom (2006) for the global star formation rate density as a function of redshift, $\dot{\rho}_*(z)$. For the Milky Way parameters, following PF02 and references therein, we use $\psi_{\mathrm{MW}} = 3.2\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ and $\mu_{\mathrm{MW}} = 0.14$. Lastly, we parametrize the Milky Way γ-ray luminosity as $L_{\gamma,\mathrm{MW}}(E) = 1.36\times10^{39}\,(E/600\,\mathrm{MeV})^{-\kappa}\,\mathrm{s}^{-1}\,\mathrm{MeV}^{-1}$, where $\kappa = 1.5$ for $E \le 600$ MeV and $\kappa = 2.7$ for $E > 600$ MeV. This parametrization comes from a broken power-law fit to the 'GALPROP conventional' (Strong, Moskalenko & Reimer 2004) model of the

[2] Here, we have explicitly assumed, unlike PF02, that most of the normal-galaxy γ-ray emissivity at a certain redshift comes from galaxies with similar γ-ray properties; it is the properties of that typical galaxy that evolve with cosmic time according to the product of the cosmic star formation rate and the gas-mass fraction histories.

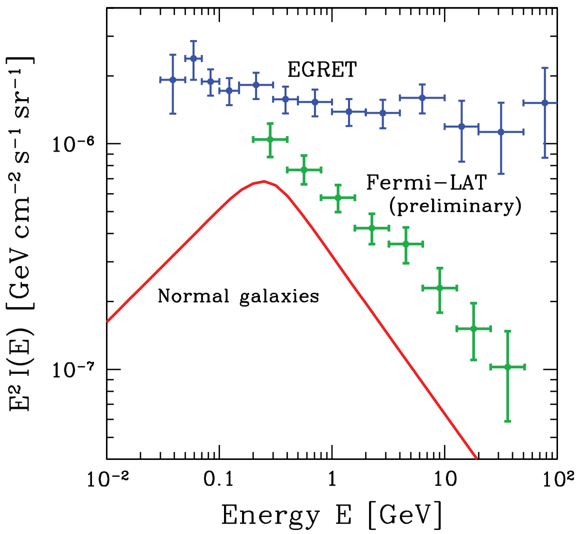

Figure 1. The CGB intensity from normal galaxies, compared with the Sreekumar et al. (1998) determination of the CGB from EGRET data and preliminary *Fermi* data.

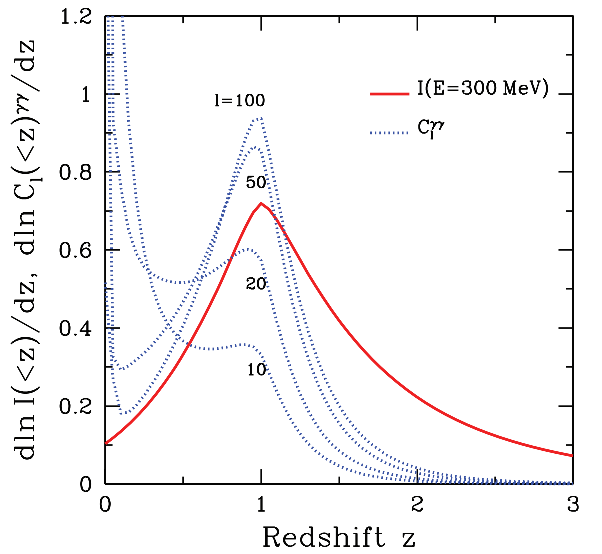

Figure 2. Contribution from unit redshift range to the mean CGB intensity at 300 MeV (solid) and angular auto-power spectrum at $\ell = 10$, 20, 50 and 100 (dotted).

energy spectrum of the diffuse Milky Way γ-ray emission (which is compatible with no GeV excess).[3] We set the normalization by requiring that the energy integral of $L_{\gamma,\mathrm{MW}}$ above 100 MeV is 2.85×10^{42} photons s^{-1} (see PF02 and references therein).

In Fig. 1, we plot, with the solid line, the γ-ray intensity $E^2 I(E)$ from normal galaxies, compared with the Sreekumar et al. (1998) determination of the CGB from EGRET data. The galaxy contribution appears to be important in particular for energies between 50 MeV and 1 GeV. We point out that due to the shift of the spectral break in the Milky Way diffuse emission spectrum from 850 MeV (which was the location of the break in EGRET data which suffered from the GeV excess) to 600 MeV (the location of the break in GALPROP conventional), the peak of the normal-galaxy contribution correspondingly shifted from ∼500 MeV in PF02 to ∼250 MeV in Fig. 1 in this work. Additionally, the contribution of normal galaxies to the CGB declines with energy above 1 GeV faster than it did in PF02, as the high-energy slope of the Milky Way spectrum adopted here (2.7) is steeper than the value implied by EGRET data (2.4) and adopted by PF02. It is worth noting that a preliminary analysis of *Fermi* data indicates that the slope of the CGB spectrum at high energies may be substantially steeper (consistent with $\sim E^{-2.45}$, see M. Ackermann for the LAT Collaboration[4]) than the EGRET measurement. To illustrate this point, in Fig. 1, we also plot the preliminary *Fermi* CGB results.

In Fig. 2, we plot, with the solid line, the integrand of equation (1) in units of the integral as a function of redshift at $E = 300$ MeV; this quantity represents the contribution to the mean CGB intensity at a given energy from galaxies in a specific redshift range. Following the evolution of the cosmic star formation rate, it peaks at $z \simeq 1$ and declines for higher redshifts.

3 ANGULAR AUTO-POWER SPECTRUM FOR THE CGB FROM NORMAL GALAXIES

The angular auto-power spectrum of the CGB map due to normal galaxies is given by

$$C_\ell^{\gamma\gamma} = \frac{c}{16\pi^2 I^2(E)} \int \mathrm{d}z \frac{\dot{n}^2_{\gamma,\mathrm{com}}[(1+z)E, z]}{H(z) r^2} P_{\mathrm{gal}}\left(\frac{\ell}{r}, z\right), \qquad (5)$$

where r is the comoving distance and $P_{\mathrm{gal}}(k, z)$ is the galaxy power spectrum at comoving wave number k and redshift z (e.g. Ando et al. 2007b). The multipole ℓ corresponds roughly to the angular scale of $\theta = 180°/\ell$. Note that we defined $C_\ell^{\gamma\gamma}$ as the variance of the fluctuation from the mean intensity in units of steradian.

The galaxy power spectrum is a well-measured quantity according to the modern galaxy surveys (e.g. Cole et al. 2005; Maller et al. 2005; Percival et al. 2007). It traces the underlying matter power spectrum. To compute the latter, we adopt the halo-model approach (Seljak 2000; Cooray & Sheth 2002) with the linear transfer function given by Eisenstein & Hu (1999), which gives a reasonable fit to the galaxy power spectrum with a moderate correction for the bias, for example $b_{\mathrm{gal}} = 1.11$ (Afshordi, Loh & Strauss 2004).

In Fig. 3(a), we show the angular auto-power spectrum $\ell\,(\ell + 1)\,C_\ell^{\gamma\gamma}/2\pi$ for $E = 300$ MeV, as a function of multipole ℓ. In the multipole range between 1 and 10^3, $\ell(\ell + 1)\,C_\ell^{\gamma\gamma}/2\pi$ ranges from 10^{-6} to 10^{-3}, which is much smaller than the case of other sources. For instance, in the case of blazars, $\ell\,(\ell + 1)\,C_\ell^{\gamma\gamma}/2\pi$ would be no smaller than $\sim 10^{-4}$ even at large angular scales. In the case of dark matter annihilation in the extragalactic haloes, it could be as large as 0.1 at $\ell = 10^3$ (Ando & Komatsu 2006; Ando et al. 2007b), or even larger in the case of annihilation in the Milky Way subhaloes (Siegal-Gaskins 2008; Ando 2009). In addition to the amplitude, the shape of the power spectrum might also serve as a diagnostic as it is also different for different source populations.

[3] Note that this is not the latest version of GALPROP that is used in the *Fermi*–LAT data analysis and in the comparison with *Fermi*–LAT data on the diffuse emission from the Galaxy. However, the anisotropy models we are discussing here are not very sensitive to the details of the input single-galaxy intensity spectrum. The aspects of the cumulative normal-galaxy intensity spectrum that affect our analysis the most are the energy of the peak, and the energies above which we are in the power-law tail of the spectrum; both these issues can be adequately treated using the simple models we adopt here, and for this reason we do not engage in a more detailed analysis of the cumulative intensity spectrum. We will return to the latter in an upcoming publication.

[4] http://www-conf.slac.stanford.edu/tevpa09/Ackermann090714v2.ppt

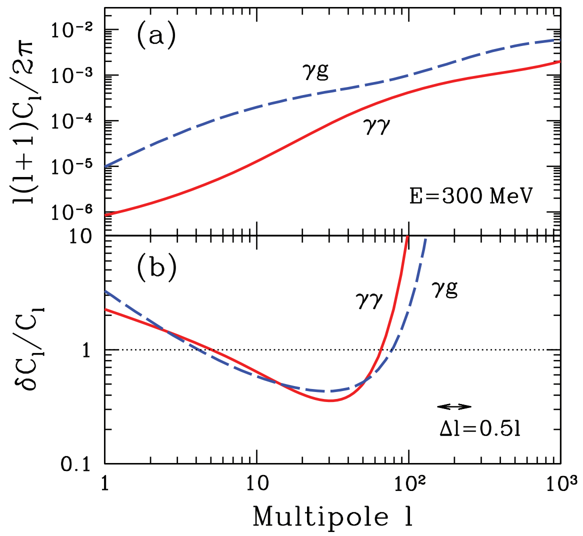

Figure 3. (a) The angular auto-power ($\gamma\gamma$; solid) and cross-power (γg; dashed) spectra for $E = 300$ MeV. The cross-correlation is taken with a 2MASS-like galaxy catalogue. (b) The relative errors of the power spectra after 5-year all-sky measurement with *Fermi*–LAT. The bin width, $\Delta\ell = 0.5\ell$, is shown as the arrowed line.

In Fig. 2, we also show the contribution to the angular auto-power spectrum from a given redshift range, i.e. $\mathrm{d}\ln C_\ell^{\gamma\gamma}/\mathrm{d}z$ (the integrand of equation 5 as a function of redshift in units of the integral) for multipoles $\ell = 10$, 20, 50 and 100, which, as we show below, are the observationally relevant scales. For large angular scales, for example $\ell = 10$ and 20, the dominant contribution comes from low redshifts mainly because of the r^{-2} dependence of the integrand in equation (5). For smaller angular scales, on the other hand, the distribution develops a second peak at $z = 1$, reflecting the dependence on the cosmic star formation rate. Therefore, in principle, we can probe different redshift ranges by observing $C_\ell^{\gamma\gamma}$ for various ℓ, even though these quantities are obtained after the redshift information is integrated out. Note that the relative contributions of different redshift ranges to $C_\ell^{\gamma\gamma}$ are also different from those to the mean intensity $I(E)$. In Fig. 4, we show the same redshift distribution for $C_\ell^{\gamma\gamma}$, but focusing on the lower redshift range $z < 0.1$. Towards larger distances, correlations of galaxies are averaged out quickly, and this effect is more prominent for large angular-scale modes as expected.

We now examine the auto-correlation detectability with the *Fermi*–LAT. The 1σ errors for $C_\ell^{\gamma\gamma}$ measurements are given by

$$\delta C_\ell^{\gamma\gamma} = \sqrt{\frac{2}{(2\ell+1)\Delta\ell f_{\rm sky}}}\left(C_l^{\gamma\gamma} + \frac{C_{\rm P}+C_N}{W_\ell^2}\right), \qquad (6)$$

where $f_{\rm sky} = \Omega_{\rm sky}/4\pi$ is the fraction of the sky measured, $\Delta\ell$ is the bin width for which we use 0.5ℓ and $W_\ell = \exp(-\ell^2\sigma_b^2/2)$ is the window function with the angular resolution $\sigma_b \approx 1\overset{\circ}{.}2$ for 300 MeV photon. The first term represents the cosmic variance and the second the shot noise due to finite statistics of galaxy ($C_{\rm P}$) and photon (C_N) counts. The Poisson noise due to galaxies $C_{\rm P}$ is obtained by equation (5) with replacement $P_{\rm gal}(k, z) \to n_{\rm gal}^{-1}$; for the comoving number density of galaxies $n_{\rm gal}$, we use 10^{-2} Mpc^{-3} and assume that it is independent of redshifts. We thus obtain $C_{\rm P} = 3.4 \times 10^{-8}$ sr. The Poisson noise due to finite photon count is given by $C_N = \Omega_{\rm sky}/N_\gamma$, where N_γ is the number of photons received from $\Omega_{\rm sky}$. We estimate $N_\gamma = EI(E)A_{\rm eff}T_{\rm eff}\Omega_{\rm sky} \approx 5.0 \times 10^6 f_{\rm sky}$, where we used $E =$ 300 MeV, $A_{\rm eff} = 6000$ cm^2, $T_{\rm eff} = T\Omega_{\rm fov}/4\pi$, $\Omega_{\rm fov} = 2.4$ sr (LAT field of view) and assumed a 5-year all-sky survey ($T = 5$ yr). Thus, we obtain $C_N = 2.5 \times 10^{-6}$ sr, which dominates the noise term due to finite galaxy counts $C_{\rm P}$. Note that the uncertainties calculated here are conservative, as we have not included the effects of smearing with energy within the assumed energy bin ($\Delta E \sim E$, with the bin extending from E to $2E$). Although the C_ℓ are independent of energy as long as we are in the power-law tail of the intensity spectrum, the angular resolution σ_b, and thus the uncertainties δC_ℓ, do depend on energy. However, since in the spectrum high-energy tail, the intensity is decreasing with energy as $\sim E^{-2.7}$, the photons in the energy bin will be dominated by the low-energy photons, and the effect of energy smearing will be small. In addition, as σ_b *decreases* with increasing energy, the inclusion of higher energy photons will result in a decrease of the overall uncertainty.

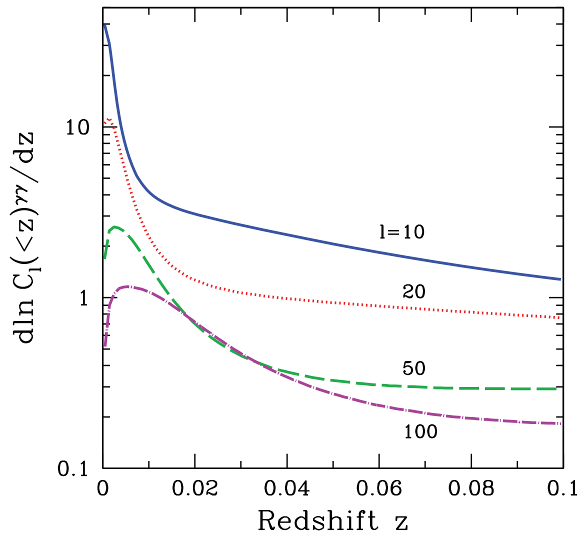

Figure 4. Same as Fig. 2, focused on low-redshift range.

In Fig. 3(b), we plot, with the solid line, $\delta C_\ell^{\gamma\gamma}/C_\ell^{\gamma\gamma}$ assuming all-sky coverage ($f_{\rm sky} = 1$). There appears to be a sweet spot between $\ell \approx 5$ and 70, where one can claim positive detection of galaxy clustering in the CGB with 5-year *Fermi* data. Below this region, as we have only $2\ell + 1$ modes for fixed ℓ, $C_\ell^{\gamma\gamma}$ cannot be constrained very well (cosmic variance). For ℓ larger than 100, corresponding to $\theta \lesssim 1°$, the errors become exponentially large because of the limited angular resolution of *Fermi*–LAT.

4 CROSS-CORRELATION WITH GALAXY CATALOGUE

We now discuss the cross-correlation between the CGB map and the existing galaxy catalogues. The angular cross-power spectrum is given by

$$C_\ell^{\gamma g} = \frac{1}{4\pi I(E) N_{\rm g}}\int \mathrm{d}z \frac{\dot n_{\gamma,\rm com}[(1+z)E, z]}{r^2}\frac{\mathrm{d}N_{\rm g}}{\mathrm{d}z} \times P_{\rm gal}\left(\frac{l}{r}, z\right), \qquad (7)$$

where we define $\mathrm{d}N_{\rm g}/\mathrm{d}z$ as the redshift distribution of galaxies and $N_{\rm g}$ is the total number of galaxies of the catalogue:

$$N_{\rm g} = \int \mathrm{d}z \frac{\mathrm{d}N_{\rm g}}{\mathrm{d}z}. \qquad (8)$$

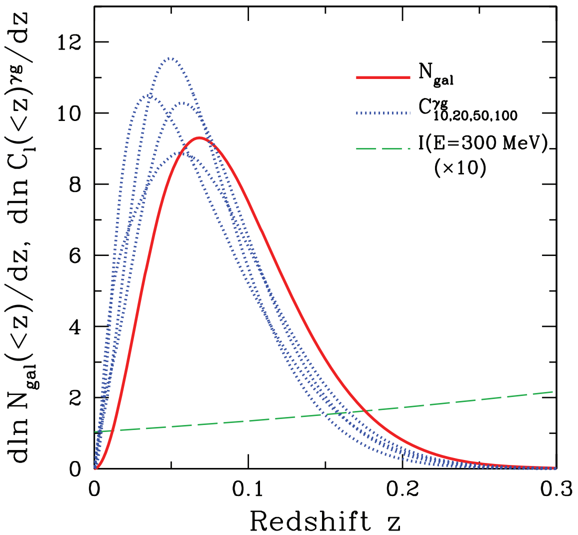

Figure 5. Redshift distribution of a 2MASS-like galaxy catalogue (solid) and angular cross-power spectrum at $\ell = 10$, 20, 50 and 100 (dotted). The redshift dependence of 10 times the mean CGB intensity is shown for comparison (dashed).

The galaxy auto-power spectrum can also be computed with these quantities as

$$C_\ell^{gg} = \frac{1}{cN_g^2} \int dz \frac{H(z)}{r^2} \left(\frac{dN_g}{dz}\right)^2 P_{gal}\left(\frac{l}{r}, z\right). \tag{9}$$

For the present study, we consider a galaxy catalogue similar to the Two-Micron All-Sky Survey (2MASS) Extended Source Catalog (Jarrett et al. 2000). This is a full sky ($f_{sky} \sim 1$), near-infrared survey of galaxies whose median redshift is around $z \sim 0.1$ and total number is $N_g \sim 10^6$. The redshift distribution d ln N_g/dz is shown as a solid curve in Fig. 5, for which we used fitting formula given in Afshordi et al. (2004).

Using this galaxy catalogue and the CGB emissivity at $E = 300$ MeV, we compute the angular cross-power spectrum $\ell(\ell+1) C_\ell^{\gamma g}/2\pi$, showing it as a dashed curve in Fig. 3(a). The amplitude of the cross-power is larger than that of auto-power by about an order of magnitude, which would make the former easier to be detected. In Fig. 5, we show contributions from unit redshift ranges to $C_\ell^{\gamma g}$ for $\ell = 10$, 20, 50 and 100 as dotted curves. Unlike the case of auto-power spectrum, the redshift distribution is fairly similar for different angular scales, because the galaxy distribution dN_g/dz has a much sharper peak than dI/dz.

The 1σ errors of the cross-power spectrum is estimated by (e.g. Zhang & Beacom 2004; Cuoco et al. 2007)

$$\delta C_\ell^{\gamma g} = \sqrt{\frac{1}{(2\ell+1)\Delta\ell f_{sky}}} \left[(C_\ell^{\gamma g})^2 + \left(C_\ell^{\gamma\gamma} + \frac{C_P + C_N}{W_\ell^2}\right)(C_\ell^{gg} + C_{N,g}) \right]^{1/2}, \tag{10}$$

where we use equation (9) for C_ℓ^{gg} in this expression; $C_{N,g} = \Omega_{sky}/N_g = 1.5 \times 10^{-5} f_{sky}$ sr is the galaxy shot noise. The errors for $C_\ell^{\gamma g}$ are plotted as a dashed curve in Fig. 3(b), which shows similar prospects to the case of auto-power spectrum, for detecting the galaxy clustering in the CGB anisotropy. The sweet spot is slightly wider than that for the auto-power spectrum.

5 DISCUSSION AND CONCLUSIONS

In the calculations for both the mean intensity and anisotropy, we assumed that the γ-ray emissivity of all galaxies at the same redshift is the same, rescaled from the emissivity of the Milky Way using the cosmic star formation rate as well as the gas-mass fraction. This implicitly assumes that all the galaxies of interest are Milky Way-like in their γ-ray properties. Although this is clearly not true for all galaxies, what it really amounts to is assuming that most γ-ray photons emitted by star-forming galaxies come from Milky Way-like, properly de-evolved sources. This in turn is not an unreasonable assumption. Milky Way-like objects are rich in both star formation and gas, so they are expected to be the most γ-ray bright among normal star-forming galaxies of the same epoch (see e.g. Pavlidou & Fields 2001). This is the reasoning behind taking, as a first approximation, all normal galaxies contributing to the CGB to have a single luminosity at a given redshift, instead of using a luminosity function.

A notable exception to this general rule is that of starburst galaxies, which, depending on the details of cosmic ray confinement, could individually be one to two orders of magnitude brighter in γ-rays than the typical Milky Way-like galaxy of the same cosmic epoch, as well as have harder energy spectra at high energies (see e.g. Thompson, Quataert & Waxman 2007). However, starburst galaxies would be best treated as a distinct source class as far as their anisotropy properties are concerned – compared to normal star-forming galaxies, the population of starburst galaxies consists of few bright sources, and the anisotropy at small angular scales could be considerably stronger even if the overall contribution of starbursts to the CGB is lower. We will return to this issue in a future publication.

Until this point, we have concentrated on photons of $E = 300$ MeV, as the γ-ray energy flux spectrum due to normal galaxies peaks at this energy (see Fig. 1). We now also discuss the results for higher energy photons $E = 1$ GeV. At this energy, although the energy flux from star-forming galaxies is lower, the LAT effective area increases to 8000 cm^2, and also the angular resolution improves to $\sim 0\overset{\circ}{.}8$ (Atwood et al. 2009). In Fig. 6, we show the same plots as Fig. 3 but for $E = 1$ GeV photons. We find that especially for the cross-correlation, the detection prospects are still pretty good even though the number of photons received would decrease. In addition,

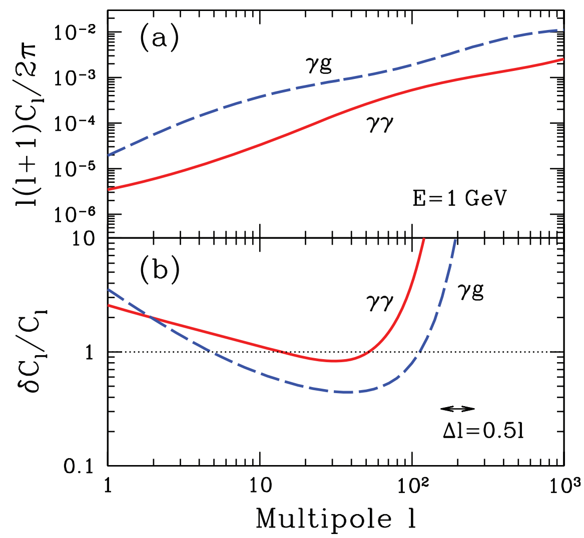

Figure 6. Same as Fig. 3, for photons of $E = 1$ GeV.

the multipole range for the detection becomes larger, above $\ell = 100$ for $C_\ell^{\gamma g}$.

Although we fixed the galaxy bias to be $b_{\rm gal} = 1.11$ throughout (Afshordi et al. 2004), the relevant value of the bias might be different. This is because while $b_{\rm gal}$ refers to all galaxies, we are not interested in elliptical galaxies, faint dwarfs or gas-poor dwarfs, which do not emit significant amount of γ-rays. Thus, the bias of star-forming γ-ray bright galaxies might differ from that of all the galaxies as inferred from galaxy catalogues. However, our results are not very sensitive to the value of $b_{\rm gal}$ as long as the true value is not significantly different from 1.

The emission from individual galaxies we have considered is entirely due to the interaction between cosmic rays and interstellar gas and light; any contribution from point sources within galaxies has not been accounted for. However, using γ-ray observations of the Milky Way for guidance, we expect that the contribution of point sources to the total γ-ray emission of a star-forming galaxy is small. First, the relative intensity of the diffuse flux is much higher than the total emission due to resolved point sources in the Milky Way (see e.g. Hartman et al. 1999). Secondly, the good agreement between the Milky Way diffuse emission as measured by *Fermi*–LAT and GALPROP, indicates that in the Milky Way point sources are not a dominant component in the diffuse emission, at least at mid-Galactic latitudes. The situation can be very different for early-type galaxies with little star formation, in which most γ-ray emission would arise from non-thermal processes in older populations of stellar remnants, such as millisecond pulsars. However, the contribution of early-type galaxies to the CGB is expected to be very small.

We also comment on the non-linear part of the galaxy power spectrum. The angular scales where such non-linearity becomes important are $\ell \approx 10^3$ for $C_\ell^{\gamma\gamma}$ and $\ell \approx 100$ for $C_\ell^{\gamma g}$. Remembering that the angular resolution of *Fermi*–LAT for 1 GeV photons corresponds roughly to $\ell \approx 100$, the non-linear part of the power spectrum does not affect the relevant result much. The reason why non-linearity becomes important at lower ℓ for the cross-power is that with the 2MASS-like galaxy catalogue, the contribution is biased to lower redshifts (compare redshift distribution in Figs 2 and 5) that correspond to larger spatial scales for fixed angular scales (note $k = \ell/r$ in the argument of galaxy power spectrum $P_{\rm gal}$).

In conclusion, motivated by the fact that normal galaxies provide a guaranteed contribution to the CGB and that *Fermi*–LAT has a good sensitivity to measure it, we have theoretically computed the CGB angular power spectrum due to normal galaxies. We have calculated both the auto-power ($C_\ell^{\gamma\gamma}$) and the cross-power ($C_\ell^{\gamma g}$) spectra, using the well-measured galaxy power spectrum; for the cross-power, we correlated the CGB with a 2MASS-like galaxy catalogue. We found that the amplitude of $C_\ell^{\gamma\gamma}$ is smaller than that for other sources such as blazars and dark matter annihilation. Still, *Fermi*–LAT can measure the significant feature of the galaxy clustering for the multipole range $10 \lesssim \ell \lesssim 100$ in about 5 years. The amplitude of the cross-power spectrum $C_\ell^{\gamma g}$ is larger, and the detection prospects are better for higher energy photons. We also found that the redshift ranges that contribute to the power spectrum the most are different from the case of mean intensity. This feature might be helpful in probing the γ-ray luminosity density from normal galaxies at various redshift ranges.

ACKNOWLEDGMENTS

We thank John Beacom and Troy Porter for insightful comments that helped improved this paper. This work was supported by Sherman Fairchild Foundation (SA) and by NASA through the GLAST Fellowship Programme, NASA Cooperative Agreement: NNG06DO90A (VP).

REFERENCES

Abdo A. A. et al., 2009, ApJ, 703, 1249
Afshordi N., Loh Y.-S., Strauss M. A., 2004, Phys. Rev. D, 69, 083524
Ando S., 2009, Phys. Rev. D, 80, 023520
Ando S., Komatsu E., 2006, Phys. Rev. D, 73, 023521
Ando S., Komatsu E., Narumoto T., Totani T., 2007a, MNRAS, 376, 1635
Ando S., Komatsu E., Narumoto T., Totani T., 2007b, Phys. Rev. D, 75, 063519
Atwood W. B. et al., 2009, ApJ, 697, 1071
Cole S. et al., 2005, MNRAS, 362, 505
Cooray A., Sheth R., 2002, Phys. Rep., 372, 1
Cuoco A., Hannestad S., Haugbølle T., Miele G., Serpico P. D., Tu H., 2007, J. Cosmol. Astropart. Phys., 4, 13
Cuoco A., Brandbyge J., Hannestad S., Haugbølle T., Miele G., 2008, Phys. Rev. D, 77, 123518
Dermer C. D., 1986, A&A, 157, 223
Dermer C. D., 2007, ApJ, 659, 958
Eisenstein D. J., Hu W., 1999, ApJ, 511, 5
Fichtel C. E., Kniffen D. A., 1984, A&A, 134, 13
Fornasa M., Pieri L., Bertone G., Branchini E., 2009, Phys. Rev. D, 80, 023518
Hartman R. C. et al., 1999, ApJS, 123, 79
Hooper D., Serpico P. D., 2007, J. Cosmol. Astropart. Phys., 6, 13
Hopkins A. M., Beacom J. F., 2006, ApJ, 651, 142
Hunter S. D. et al., 1997, ApJ, 481, 205
Inoue Y., Totani T., 2009, ApJ, 702, 523
Jarrett T. H., Chester T., Cutri R., Schneider S., Skrutskie M., Huchra J. P., 2000, AJ, 119, 2498
Kniffen D. A., Hartman R. C., Thompson D. J., Fichtel C. E., 1973, ApJ, 186, L105
Lee S. K., Ando S., Kamionkowski M., 2009, J. Cosmol. Astropart. Phys., 7, 7
Maller A. H., McIntosh D. H., Katz N., Weinberg M. D., 2005, ApJ, 619, 147
Mayer-Hasselwander H. A. et al., 1982, A&A, 105, 164
Miniati F., Koushiappas S. M., Di Matteo T., 2007, ApJ, 667, L1
Narumoto T., Totani T., 2006, ApJ, 643, 81
Pavlidou V., Fields B. D., 2001, ApJ, 558, 63
Pavlidou V., Fields B. D., 2002, ApJ, 575, L5 (PF02)
Percival W. J. et al., 2007, ApJ, 657, 645
Prodanović T., Fields B. D., 2008, J. Cosmol. Astropart. Phys., 9, 3
Ritz S. M., Gehrels N., McEnery J. E., Meegan C., Michelson P. F., Thompson D. J., Fermi Mission Team, 2009, Am. Astron. Soc. Meeting Abs., 213, 468.01
Seljak U., 2000, MNRAS, 318, 203
Siegal-Gaskins J. M., 2008, J. Cosmol. Astropart. Phys., 10, 40
Siegal-Gaskins J. M., Pavlidou V., 2009, Phys. Rev. Lett., 102, 241301
Sreekumar P. et al., 1998, ApJ, 494, 523
Stecker F. W., 1970, Ap&SS, 6, 377
Stecker F. W., 1973, ApJ, 185, 499
Stecker F. W., Salamon M. H., 1999, in Kieda D. B., Salamon M. H., Dingus B. L., eds, Proc. 26th Int. Cosmic Ray Conf. Vol. 3, p. 313
Strong A. W., Moskalenko I. V., Reimer O., 2000, ApJ, 537, 763
Strong A. W., Moskalenko I. V., Reimer O., 2004, ApJ, 613, 956
Taoso M., Ando S., Bertone G., Profumo S., 2009, Phys. Rev. D, 79, 043521
Thompson T. A., Quataert E., Waxman E., 2007, ApJ, 654, 219
Zavala J., Springel V., Bcylan-Kolchin M., 2009, MNRAS, submitted (arXiv:0908.2428)
Zhang P., Beacom J. F., 2004, ApJ, 614, 37

This paper has been typeset from a TEX/LATEX file prepared by the author.